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Key Points:
- Tremor signal accompanied slow slip event
- Tremor activity accelerated before the 2011 Tohoku-Oki earthquake
- Possible tremor source located near the trench within coseismic slip area

Supporting Information:
- Figures S1–S3

Correspondence to:
Y. Ito,
ito.yoshihiro.4w@kyoto-u.ac.jp

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Episodic tremor and slip near the Japan Trench prior to the 2011 Tohoku-Oki earthquake

Yoshihiro Ito[1], Ryota Hino[2], Syuichi Suzuki[3], and Yoshiyuki Kaneda[4]

[1]Disaster Prevention Research Institute, Kyoto University, Uji, Japan, [2]International Research Institute of Disaster Science, Tohoku University, Sendai, Japan, [3]Department of Geophysics, Tohoku University, Sendai, Japan, [4]Disaster Mitigation Research Center, Nagoya University, Nagoya, Japan

Abstract Change in the rates of aseismic deformation prior to large earthquakes is a major area of interest in earthquake physics. Here we present evidence that episodic tremor and slip occurred in the shallow subduction zone within the source region of the 2011 Tohoku-Oki earthquake prior to the main shock. Ocean bottom seismometers near the Japan Trench recorded some excitations in amplitude of ambient noise level accompanying both the 2008 and 2011 slow slip events. The observed signals show that low frequencies of 5–8 Hz dominated, suggesting that the excitations were due to small low-frequency tremors accompanying the slow slip events. The largest amplitude tremor was observed just before the 2011 event. The estimated sources of tremors were possibly distributed within the coseismic slip area of the 2011 event, suggesting the shallow plate-boundary thrust near the trench is a general location of slow earthquakes.

1. Introduction

Understanding the changes in rates of transient deformation prior to large earthquakes in subduction zones is critical for predicting impending earthquakes and tsunamis. Some slow slip events (SSEs) and intense foreshock triggered by SSEs have been reported prior to megathrust events [e.g., *Kato et al.*, 2012; *Ito et al.*, 2013; *Ruiz et al.*, 2014; *Schurr et al.*, 2014]. Specifically, prior to the 11 March 2011 Tohoku-Oki earthquake, two possibly distinct SSEs were observed through changes in the deformation rate at the plate boundaries, which consequently triggered the main shock sequence [*Kato et al.*, 2012; *Ohta et al.*, 2012; *Ito et al.*, 2013]. The first SSE, which began at the end of January 2011, was accompanied by swarm-like interplate seismicity, and it continued until the occurrence of the largest foreshock on 9 March 2011 [*Ito et al.*, 2013]. The second SSE involved an afterslip of the largest foreshock, which occurred approximately 20 km northeast of the main shock epicenter on 11 March 2011 [*Kato et al.*, 2012; *Ohta et al.*, 2012]. Both SSEs were located in the trenchward or shallower portion of the epicenter of the main shock.

In the 2011 Tohoku-Oki earthquake, the shallow plate-boundary thrust at the Japan Trench slipped tens of meters to generate a devastating tsunami [e.g., *Ide et al.*, 2011; *Iinuma et al.*, 2012]. In particular, a large slip of >50 m was observed by geodetic and topographic measurements [*Fujiwara et al.*, 2011; *Ito et al.*, 2011]. The cause of the large coseismic slip on the shallow plate-boundary thrust remains uncertain. However, based on borehole observations and an experiment using fault material retrieved from the shallow plate-boundary thrust in the Japan Trench, *Fulton et al.* [2013] and *Ujiie et al.* [2013] demonstrated that a primary cause of the large slip was a very low coefficient of friction. *Cubas et al.* [2013] also proposed that a low effective basal friction along the large shallow slip area of the 2011 event were required from the morphology and internal structure of the fore arc.

At several subduction zones around the world, SSEs have been commonly observed to be accompanied by tectonic tremors [*Rogers and Dragert*, 2003; *Obara et al.*, 2004], phenomena referred to as "episodic tremor and slip" (ETS). SSEs and tremors are both end-members of the slow-earthquake family [*Ide et al.*, 2007], and events within this family are classified by the scale and dominant frequency of the source spectra of the events. However, there have been no published reports on the low-frequency tremor activity that accompanied the SSEs prior to the 2011 Tohoku-Oki earthquake.

Here we investigate low-frequency tremor activity accompanying SSEs prior to the 2011 Tohoku-Oki earthquake using ocean bottom seismometers deployed just above the coseismic slip area of the 2011 Tohoku-Oki earthquake before the main shock occurred.

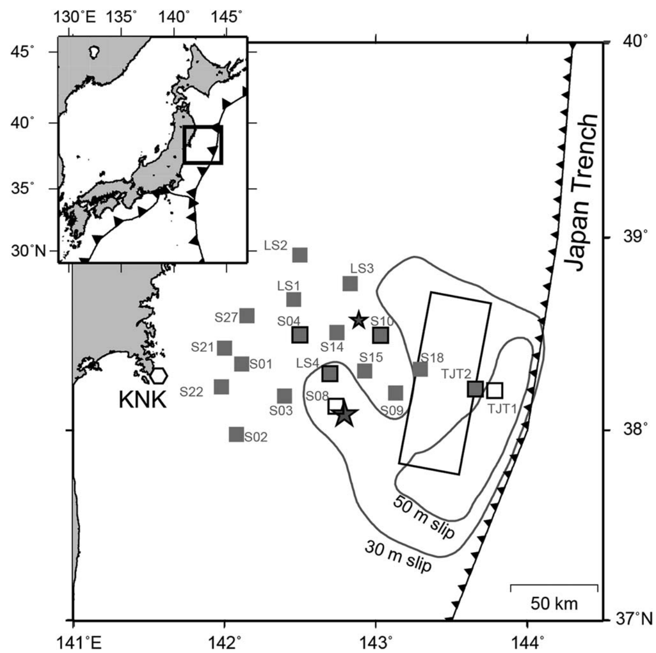

Figure 1. Map of the ocean bottom seismometer (OBS) network (open and gray squares). Large and small stars indicate the epicenters of the 11 March 2011 *M*9.0 Tohoku-Oki earthquake and its largest foreshock (*M*7.3, 9 March 2011). Open squares indicate OBSs available only on 16 October 2008. Simple gray squares indicate OBSs available on 1 December 2010. Gray squares with black border indicate OBSs available in both periods of 2008 and 2011. Hexagon indicates atmospheric pressure observation site at Station KNK. Rectangle shows the slow slip area calculated from ocean bottom pressure data and onshore geodetic data [*Ito et al.*, 2013]. The two contours show the coseismic slip areas of 30 and 50 m that originated during the 2011 Tohoku-Oki earthquake, as calculated from onshore and offshore geodetic data, respectively [*Iinuma et al.*, 2012].

2. Ocean Bottom Seismometer Network

To identify tectonic tremor activity accompanying the SSEs, we used three-component continuous seismograms in an ocean bottom seismometer (OBS) network. The OBS network was deployed above the slow slip fault on the landward slope of the Japan Trench in northeast Japan before the 2011 Tohoku-Oki earthquake (Figure 1). Short-period OBSs with a natural frequency of 1 or 4.5 Hz were used to measure the tremor signal. The recording system comprised a 24 bit analogue-to-digital converter and a hard drive. The OBSs can continuously record one vertical component and two horizontal components for 6 months at a sampling rate of 100 or 125 Hz. The water depth at the stations ranged from 1000 to 5500 m.

3. Increases in Amplitude of Ambient Noise Prior to the 2011 Tohoku-Oki Earthquake

Anomalous amplitude of ambient noise or tremor was observed at some stations near the trench, especially TJT2, just prior to the Tohoku-Oki earthquake's largest foreshock on 9 March 2011 (Figure 2). The signals were observed clearly at station TJT2, located closest to the trench at a distance of 35 km. However, it was difficult to identify significant coherent signals at other stations, although weak coherent signals with duration of approximately 3 min were observed at around 11:34 on 9 March 2011 at each station. The amplitude of the signals was largest at TJT2 and S18, located near the trench, and it decreased at stations closer to land, which suggests that the source of the signals was located near the trench.

The average dominant frequency of the ambient noise was 5–8 Hz prior to the largest foreshock (Figure 3). The signals exhibited apparent spectral roll-off at station TJT2 from 4 to 6 Hz to a lower frequency, which was related to the seismometer's natural frequency of 4.5 Hz. A comparison with the usual ambient noise levels observed at station S18 (the second closest station to the trench at 67 km) revealed a very weak signal with insignificant amplitude, nearly the same as that of the noise, at ~8 Hz on the seismometer that has a natural frequency of 4.5 Hz. Thus, our results suggest that the observed tremors with dominant frequencies of <8 Hz were excited trenchward rather than landward.

4. Root Median Square Envelopes and Their Ratios

The temporal variations of the amplitude of the ambient noise were investigated with root "median" square (RMS) envelopes of the two horizontal components at each station and their ratios between stations (Figure 4). We calculated the median within a time window of 600 s. The RMS envelope is expected to contain mainly *S* wave energy radiated from local tremor activity, local and regional ordinary seismicity, and that from other sources, such as oceanographic noise from stormy weather [*Davy et al.*, 2014].

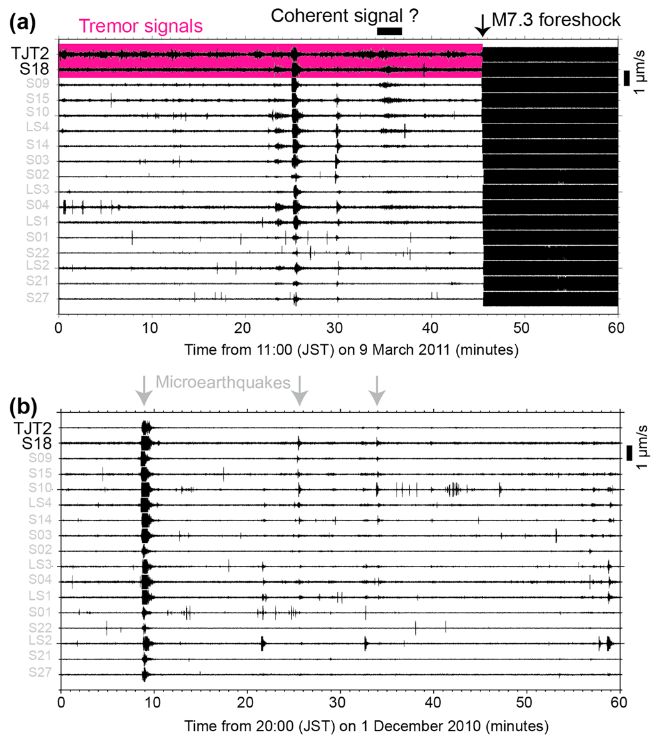

Figure 2. One hour seismograms observed by OBSs: (a) from 11:00 (JST) on 9 March 2011 and (b) from 20:00 (JST) on 1 December 2010. Continuous raw seismograms for one horizontal component filtered with cutoff frequencies of 1 and 10 Hz are plotted.

Some simultaneous excitations of envelopes were observed at some stations (Figure 4a). These events were likely due to other regional earthquakes, such as the *M*7.4 Chichi-Jima earthquake that occurred 1200 km south of the OBS network on 22 December 2010 and its aftershocks, and transient storms that lowered the atmospheric pressure above the OBS sites on 1 January 2011. Simultaneous excitations that were more "spikey" than in 2008 (Figure S1a in the supporting information) were identified at all stations during the observation period 100 days before the 2011 Tohoku-Oki earthquake (Figure 4a). This suggests that the increase in background regional seismicity in 2011 was comparable with the seismicity in 2008.

We investigated the ratio of two envelopes in order to remove the effects of regional earthquakes and stormy weather, using one station as a reference site. After applying a simple moving average with window length of 2 h, we identified three approximately triangular-shaped excitations with durations exceeding 3 days on the envelope ratio of TJT2/LS2 between 25 January and 9 March 2011, prior to the Tohoku-Oki earthquake (Figure 4b). The three excitations were clearly identifiable even if alternative reference sites were used (Figure S2). Almost all the spiky signals on the original envelopes, common to all stations, were removed after taking the ratio; however, some spikey signals with duration $<$1 day remained, especially for S15/LS2 and S18/LS2. Such short-duration signals were mostly not observed at the other stations within 20 km, and therefore, they were not recognized as tremor signals in the present situation, although this remains open to question.

Similar triangular-shaped excitations of tremors were identified at the beginning of and during the SSEs detected by ocean bottom geodetic observations at Stations TJT1 and TJT2 in 2008 [*Ito et al*., 2013], when slow slip was identified from ocean bottom observations (Figure S1). The 2008 SSE induced the *M*6.1 thrust event [*Ito et al*., 2013]. Using S14 as a reference site, coherent triangular-shaped excitations of tiny amplitude were observed at the beginning of the SSE at both TJT1 and TJT2, which are located 23 and 35 km landward from the trench, respectively, although some spikey signals after the induced *M*6.1 earthquake were observed (Figure S1b). Because data from Station TJT1 were unavailable in 2011, such triangular-shaped excitations were probably only observed at TJT2 in 2011.

The first excitation began on 25 January 25 and continued for approximately 4 days (Sequence 1). The second excitation lasted for approximately three days beginning on 16 February 2011 (Sequence 2). Finally, the third excitation occurred over the 2–3 days prior to the earthquake's largest foreshock (*M*7.3) on 9 March 2011 (Sequence 3), in which an anomalous increase of ambient noise or tremor was identified, as mentioned in the previous section. One possible cause for such an increase in ambient noise is the increase of regional microseismicity or aftershock sequences that accompany large earthquakes. However, the seismicity of the ordinal earthquakes over the three activity periods did not increase significantly (Figure 4c), suggesting that the background seismicity of ordinary microearthquakes did not contribute to the increasing amplitude of the envelope at Station TJT2.

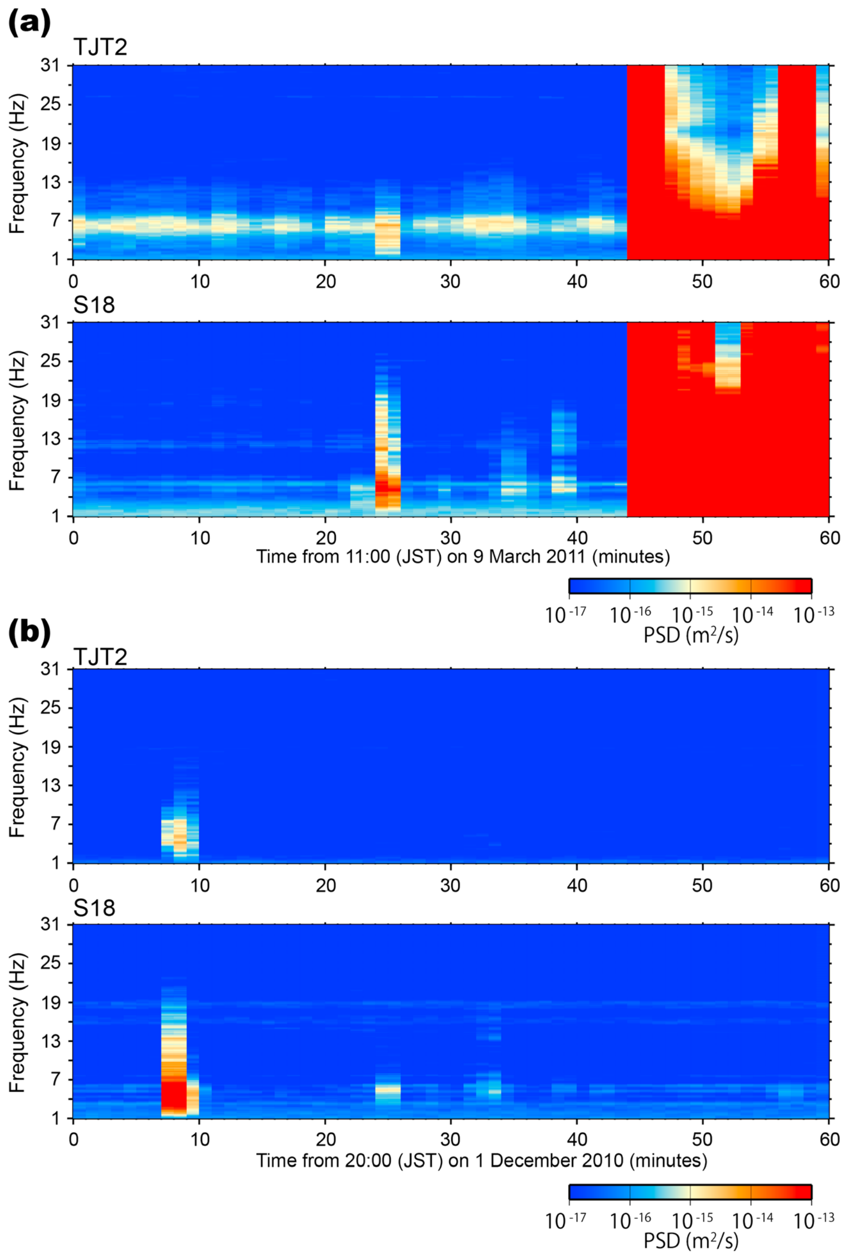

Figure 3. Spectrogram of the horizontal components for two stations (TJT1 and S18) over 1 h. Power spectral densities over 120 s within each time window are shown. (a) One hour spectrogram at 11:00 (JST) on 9 March 2011; (b) 1 h spectrogram at 20:00 (JST) on 1 December 2010.

These excitations accompanied the SSEs that had been detected by ocean bottom geodetic observations near the trench, especially Station TJT2, prior to the largest foreshock on 9 March 2011 [*Ito et al.*, 2013], and they showed that low frequencies of 5–8 Hz dominated (Figure S3). In view of the instrument response of the OBSs, the frequency components of the observed tremors are consistent with those of tectonic tremor signals detected in various subduction zones [*Ide et al.*, 2007]. This suggests that the excitations accompanying the SSEs could have been due to small low-frequency tremors associated with episodic SSEs, i.e., ETS.

5. Approximation of Possible Tremor Source Location

The tremor amplitude in three sequences at TJT2 was not usually less than 3 times the background noise level observed at S18 in 2011. However, it was difficult to calculate precisely the location of the tremor source,

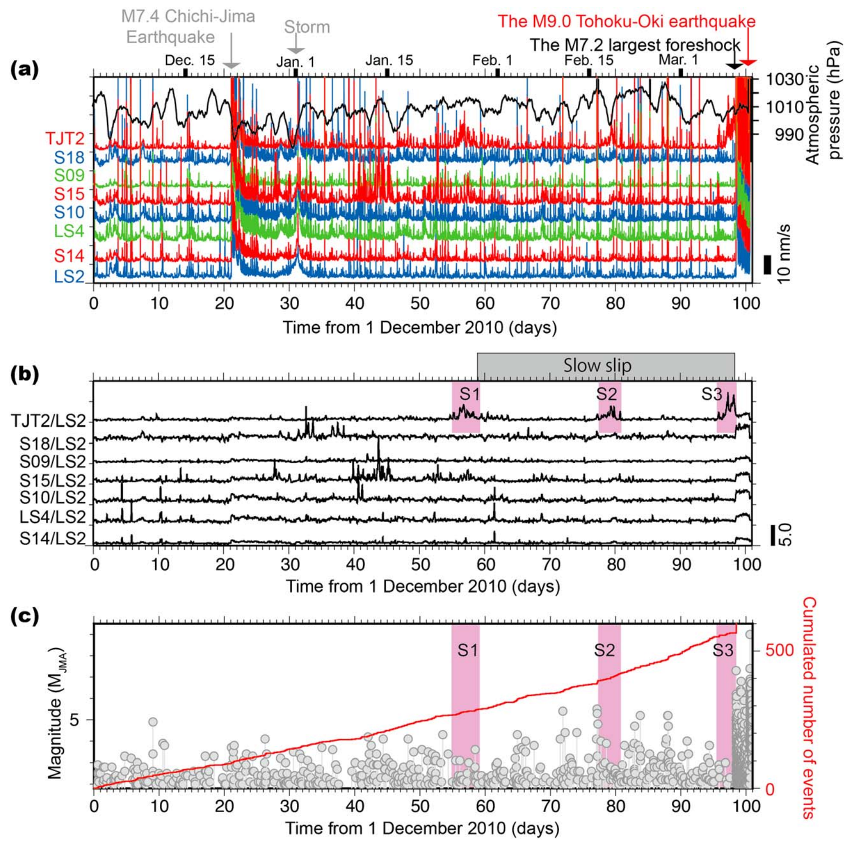

Figure 4. (a) Root median square (RMS) envelope (red, blue, and green) seismograms and atmospheric pressure observed at KNK from 1 December 2010 to 11 March 2011. RMS envelopes for the filtered outputs, determined using a band-pass filter with cutoff frequencies of 2 and 10 Hz, are plotted. (b) Envelope ratios referred to station LS2. Purple-shaded windows indicate triangular-shaped excitations observed at Station TJT2. S1, S2, and S3 correspond to Sequences 1, 2, and 3, respectively, in the text. (c) Magnitude-time plot and cumulated number of seismicity with magnitude >2 within the area shown in Figure 1 from 1 December 2010 to 11 March 2011.

because the typical tremor amplitude was insufficient to be observed at other stations. A possible location for the tremor source was approximated based on the tremor amplitude ratio observed at the two stations as TJT2/S18.

To approximate the tremor source on a two-dimensional vertical cross section perpendicular to the trench, we assumed that the tremor signals observed as *S* wave radiated isotropically from the plate-boundary thrust with dip angle of 9° (Figure 5a), which was based on seismic survey data [*Tsuji et al.*, 2011]. This assumption was employed because typical tectonic tremor signals observed at other subduction zones have primarily been composed of body waves radiated from the plate-boundary thrust [*Shelly et al.*, 2006, 2007]. Assuming that the geometrical attenuation of the radiated energy of the body waves from the tremor source was inversely proportional to the square of the distance from the source, we calculated the tremor amplitude ratio of TJT2/S18 (γ) as a function of the horizontal distance (x) from the trench as follows:

$$\gamma = \sqrt{\left((x - x_2)^2 + x^2\tan^2\theta\right) / \left((x - x_1)^2 + x^2\tan^2\theta\right)} \tag{1}$$

where $x_1 = 35$ km and $x_2 = 67$ km are the distances of TJT2 and S18 from the trench, respectively, and θ indicates the dip angle of plate-boundary thrust. We simply ignored amplification due to the free-surface effect in equation (1). Because the observed tremor amplitude ratio of TJT2/S18 is not less than 3, the possible horizontal distance of tremor source was estimated to be within a range of approximately 20–40 km, suggesting that the tremor source was located beneath or seaward of Station TJT2 (Figure 5).

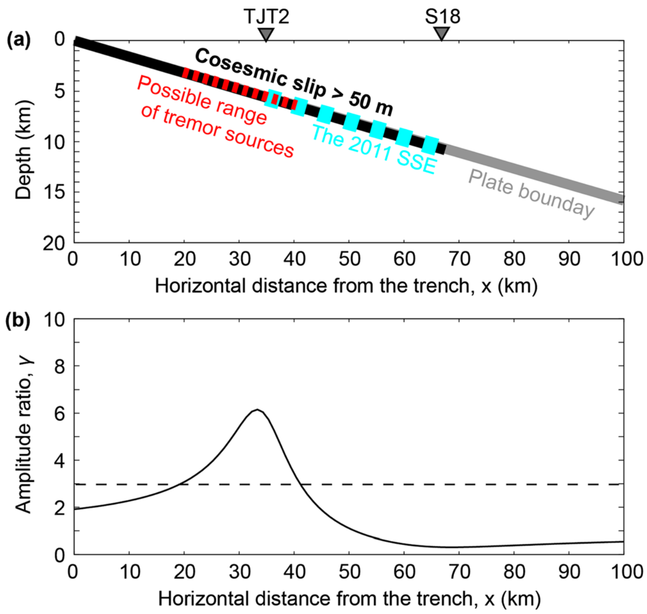

Figure 5. (a) Two-dimensional model to calculate tremor source and calculate possible range of tremor sources (red broken line). Inverted triangles indicate horizontal positions of stations TJT2 and S18. Black and broken light blue lines indicate coseismic slip >50 m in the 2011 Tohoku-Oki event and the 2011 slow slip area [*Iinuma et al.*, 2012; *Ito et al.*, 2013]. (b) Amplitude ratio calculated from model shown in Figure 4a. Amplitude ratio of tremor signals of TJT2/ S18 is not less than 3, which is shown by the broken line.

6. Discussion and Conclusions

We demonstrated that anomalous tremors were recorded by seismometers located within 35 km from the trench. The largest excitation of tremors was observed near the trench just before the largest foreshock of the main shock of the 2011 Tohoku-Oki earthquake. The possible source areas of the tremors were located approximately around the updip portion of the 2011 SSE fault prior to the largest foreshock and the main shock [*Ito et al.*, 2013], and a large coseismic slip area that exceeded 50 m [*Iinuma et al.*, 2012] (Figure 5). Ocean bottom pressure data indicated subsidence of 4 cm at Station TJT1, located 23 km from the trench, after 15 February 2011 [*Hino et al.*, 2014]. On 15 February 2011, the second sequence of tremor activity was also observed at the stations near the trench. The third sequence of tremor activity with the largest amplitude was observed over the 2–3 days prior to the earthquake's largest foreshock (*M*7.3). While it is difficult to verify whether the third sequence ended after the occurrence of the largest foreshock because aftershocks of the foreshock increased the ambient noise level at all the OBS stations, these results suggest that the ETS primarily occurred and accelerated within the source region of the 2011 Tohoku-Oki earthquake prior to the foreshock or the main shock.

Our observations in both 2008 and 2011 suggest that the shallow plate-boundary thrust near the trench can be characterized as a general location of slow earthquakes, because SSEs and tremors (both end-members of the slow-earthquake family) were observed [*Ide et al.*, 2007]. This suggests that the shallow plate interface should promote stable slip and damp coseismic rupture of a megathrust event. However, there is the contradiction that the coseismic rupture in the 2011 Tohoku-Oki event found the stresses needed to reach its peak slip during the main shock. One possible explanation to reconcile the large coseismic slip at the location of the slow earthquakes is through thermal pressurization [e.g., *Sibson*, 1973]. Alternatively, dynamic weakening related to the occurrence of SSEs prior to coseismic rupture is another possible mechanism for the coexistence of both slow and fast ruptures. Further studies based on frictional experiments using actual fault samples [e.g., *Ujiie et al.*, 2013] or numerical simulations are required to explain the coexistence of both slow earthquakes and coseismic rupture in the megathrust event [e.g., *Noda and Lapusta*, 2013].

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